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LARGE-ARRAY SIGNAL AND NOISE ANALYSIS

Special Scientific Report No. 22

EXTRACTION OF LONG-PERIOD RAYLEIGH WAVES FROM AMBIENT NOISE

Prepared by
Dr. Wayne W. Wilkins

Frank H. Binder, Program Manager

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract No. AF 33(657)-16678

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

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Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
ARPA Order No. 599
AFTAC Project No. VT/6707

16 September 1968

42

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTD)

LIST OF TABLES

SECTION I
INTRODUCTION

This report presents the results of an investigation of processing techniques for extracting long-period Rayleigh waves from ambient noise by using various geometries of the LASA long-period vertical array. Various types of noise fields, array configurations, and signal models are used. Delay-and-sum and multichannel signal extraction are the processing schemes which are evaluated for their relative effectiveness in extracting Rayleigh waves. Effectiveness is based on noise-power reduction and signal preservation. By processing the signal and noise separately, the amount of noise-power reduction and the degree of signal preservation can be assigned individually.

Results indicate that

- For a given array geometry, the multichannel signal-extraction filter gives greater noise-power rejection than the corresponding beamsteer processor. For a small array (60 km or less) having few elements, MCF gain over summation processing is very significant; below approximately 0.1 Hz, gain is 3 to 10 db

- For small-aperture arrays (less than 60 km), beamsteering does not give $\sqrt{N}$ (N= number of elements) amplitude rejection of noise below 0.1 Hz; furthermore, beamsteering of this type of array can sometimes produce adverse effects due to large sidelobes in the beamforming gain pattern

- The 9-channel MCF (A0, C and D rings) is significantly superior to the 5-channel MCF (A0 and C ring or A0 and D ring)

- Addition of sensors outside a 9-channel 60-km array gives very little additional noise rejection when using MCF processing
- Use of a dispersive signal model in the multichannel filter design yields no significant improvement over the use of a nondispersive model
- For point-like noise sources, the noise-reduction capabilities of each processor are a function of signal and noise azimuthal separation, being generally least for small separation
- Signal distortion appears negligible for all processors studied

SECTION II
DATA SELECTION AND PREPARATION

Generally, in designing a multichannel signal-extraction filter, noise statistics are developed from a portion of the ambient noise immediately preceding the event. Due to a lack of adequate noise samples proximate in time to events in TI's library, it was necessary to imbed events having high signal-to-noise ratios in 80-min ambient noise samples. No actual imbedding took place, however, since processing of signal and noise separately permitted separate evaluations of signal preservation and noise-power reduction.

Three 80-min long-period noise samples recorded at LASA during winter months were selected for processing. Three events were also chosen for imbedding – one for each noise sample. Each combination of noise and event was selected so as to simulate a particular processing environment. Table II-1 lists each noise and event combination and its most dominant characteristics.

The 80-min noise samples were available with a 1-sec sampling interval. Before the noise sample was processed, the means were removed and the data resampled to a 2-sec sampling interval. Similarly, event data were resampled to a 2-sec interval following removal of means.

Because the vertical long-period sensors have been found to have considerably lower noise level than the horizontal sensors, only vertical-component processing was investigated. Array geometries were selected from combinations of A0 and the C, D, and E rings.

Table II-1

SIGNAL/NOISE PAIR CHARACTERISTICS

Event	Characteristics	Noise Sample	RMS Value of A0 Vertical Noise (digital units)
California 11 Nov 1966 (17:33:03.7-18:53:03.1)	Point-like noise source, large signal/noise azimuthal separation	3 Dec 1966 (05:37:00.5-06:56:59.9)	20
Hokkaido 12 Nov 1966 (12:30:02.5-13:50:02.5)	Point-like noise source, small signal/noise azimuthal separation	7 Feb 1967 (20:34:02.4-21:54:01.8)	33
New Hebrides 23 Nov 1966 (02:28:32.8-03:48:31.7)	Noise source broadly distributed azimuthally	13 Dec 1966 (13:02:01.6-14:22:01.0)	10

Noise-sample selection was influenced by a study of long-period winter noise samples presented in a previous report.* Certain results of that investigation are utilized in this report at appropriate points in the discussion.

*Texas Instruments Incorporated, 1967: Analysis of Long-Period Noise, Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. No. 12, Contract AF 33(657)-16678, 18 Oct.

SECTION III
PROCESSOR DESIGNS

A. BEAMSTEER

For the beamsteer processors, delays were those calculated for a wave traveling at 3.5 km/sec over the great circle path from the published epicenter of the event. The delays to the nearest 1-sec time interval were introduced into both the signal and noise data.

B. MULTICHANNEL SIGNAL EXTRACTION

Multichannel signal-extraction filters were designed in the time domain. Noise statistics were developed from the raw zero-mean noise sample. Signal models were generated from the Bartlett-smoothed power spectrum of the A0 vertical noise. Delays were introduced into the frequency domain to allow generation of a dispersive model. The delays were those calculated, to the nearest 1-sec interval, from the signal azimuth and a dispersion curve (Figure III-1) for LASA.* Following introduction of the delays, a signal-model crosspower matrix was formed and then transformed to yield the signal-model auto- and crosscorrelations. For each model generated, the number of equally spaced positive frequencies corresponded to the number of filter points per channel.

Nondispersive signal models were generated in the same manner as the dispersive model except for the fixed-velocity-vs-frequency relation. The same velocity as that used in beamsteer processing (3.5 km/sec) was chosen; this velocity corresponds to a frequency of 0.05 Hz on the dispersion curve.

*Texas Instruments Incorporated, 1967: Continuation of Basic Research in Crustal Studies, Final Rpt., Contract AF 49(638)-1588, 15 Jul.

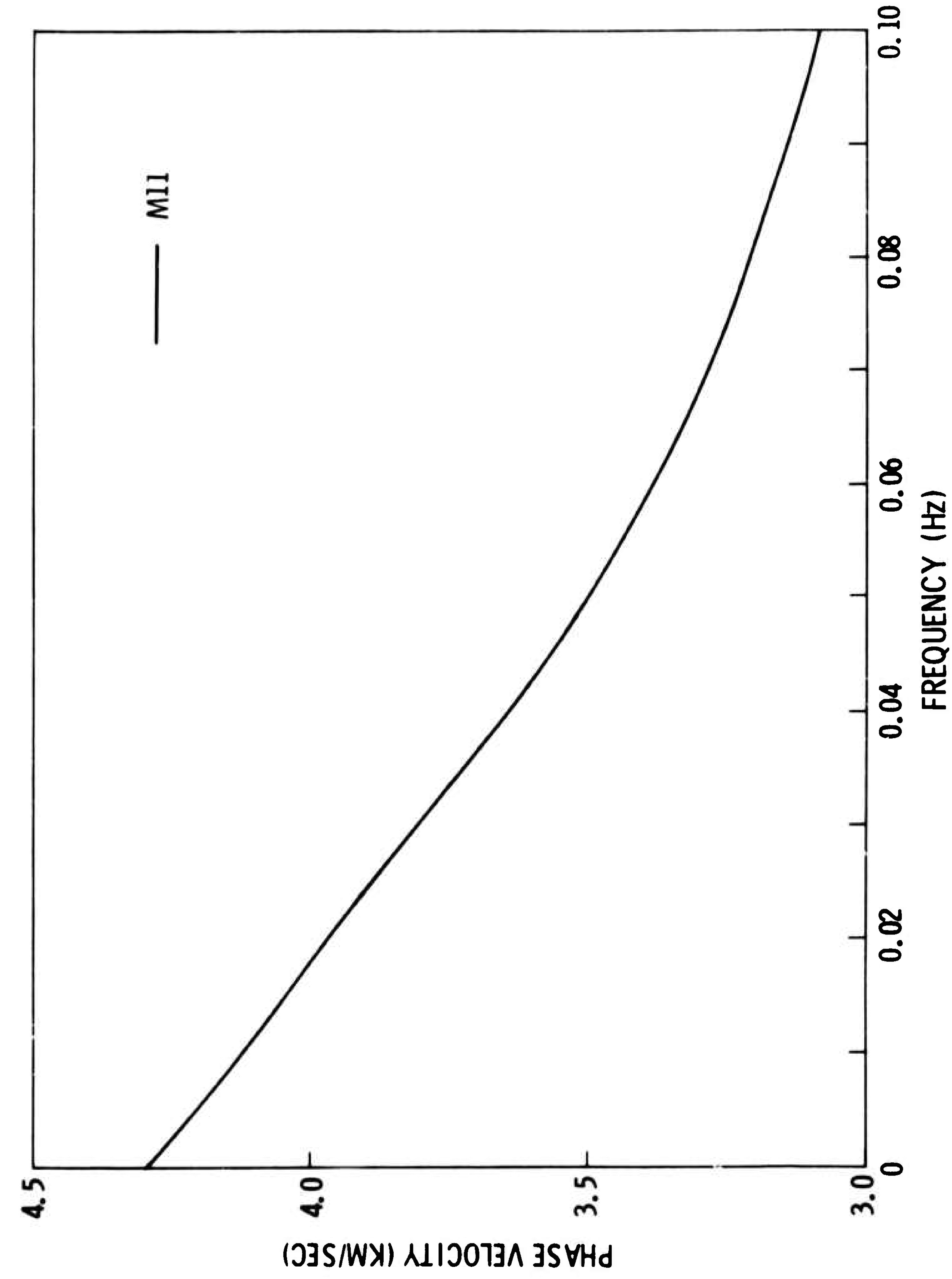

Figure III-1. Dispersion Curve for Model of LASA Crust

In one instance, the signal model was generated from the power spectrum of A0 vertical prewhitened by a 7-point deconvolution filter.

Table III-1 is a complete list of the MCF processors. In all cases, the MCF processors were designed using a signal-to-noise ratio of 4 and a statistical gain fluctuation of 1 percent (signal autopowers multiplied by 1.01).

Table III-1

MCF PROCESSORS

Filter No.	Noise Sample	Event	Event Azimuth (°)	Signal-Model Type	A0 Vertical Prewhitened	Filter Points	No. of Channels	Seis. Used
1-A	3 Dec 1966	California	254	Dispersive	No	31	5	A0, D ring
1-B	3 Dec 1966	California		Nondispersive	Yes	31	5	A0, D ring
1-C	3 Dec 1966	California		Dispersive	Yes	31	5	A0, D ring
2-A	7 Feb 1967	Hokkaido	~313	Dispersive	No	21	5	A0, C ring
2-B	7 Feb 1967	Hokkaido		Dispersive	No	21	9	A0, C, D ring
2-C	7 Feb 1967	Hokkaido		Nondispersive	No	21	5	A0, C ring
2-D	7 Feb 1967	Hokkaido		Nondispersive	No	21	9	A0, C, D ring
3-A	13 Dec 1966	New Hebrides	~257	Dispersive	No	21	5	A0, C ring
3-B	13 Dec 1966	New Hebrides		Dispersive	No	21	9	A0, C, D ring
3-C	13 Dec 1966	New Hebrides		Dispersive	No	21	12	A0, C, D, E ring
3-D	13 Dec 1966	New Hebrides		Nondispersive	No	21	5	A0, C ring
3-E	13 Dec 1966	New Hebrides		Nondispersive	No	21	9	A0, C, D ring
3-F	13 Dec 1966	New Hebrides		Nondispersive	No	21	12	A0, C, D, E ring

SECTION IV
PRESENTATION OF RESULTS

A. METHOD OF PRESENTATION

The designed processors were applied separately to signal and noise samples.

Results of noise processing are presented as plots of each processor's output power-density spectrum. The power density is plotted in db relative to an arbitrary but fixed level. The spectra are obtained by transforming 31-lag 1-sided autocorrelation functions using Bartlett smoothing.

Results of signal processing are presented in the form of wiggly-trace playbacks of processor outputs.

B. LARGE NOISE/SIGNAL AZIMUTHAL SEPARATION

Many noise samples in TI's library which were recorded at LASA during the winter months exhibit similar features in that the predominant noise originates from a point-like source and propagates at surface-wave velocities. The 3 December noise sample is typical in these respects.

Figure IV-1 shows the wavenumber spectrum of the noise obtained from the full vertical array at 0.06 Hz; the source is located at approximately N40°E and has a velocity of about 3.5 km/sec. Figure IV-2 shows a 600-sec segment of the noise. The power-density spectrum of the A0 vertical is included in Figure IV-3; a major portion of the power is concentrated in the vicinity of 0.06 Hz.

The signal is shown in Figure IV-4. This signal is relatively strong, is of short duration, and has good similarity across the array.

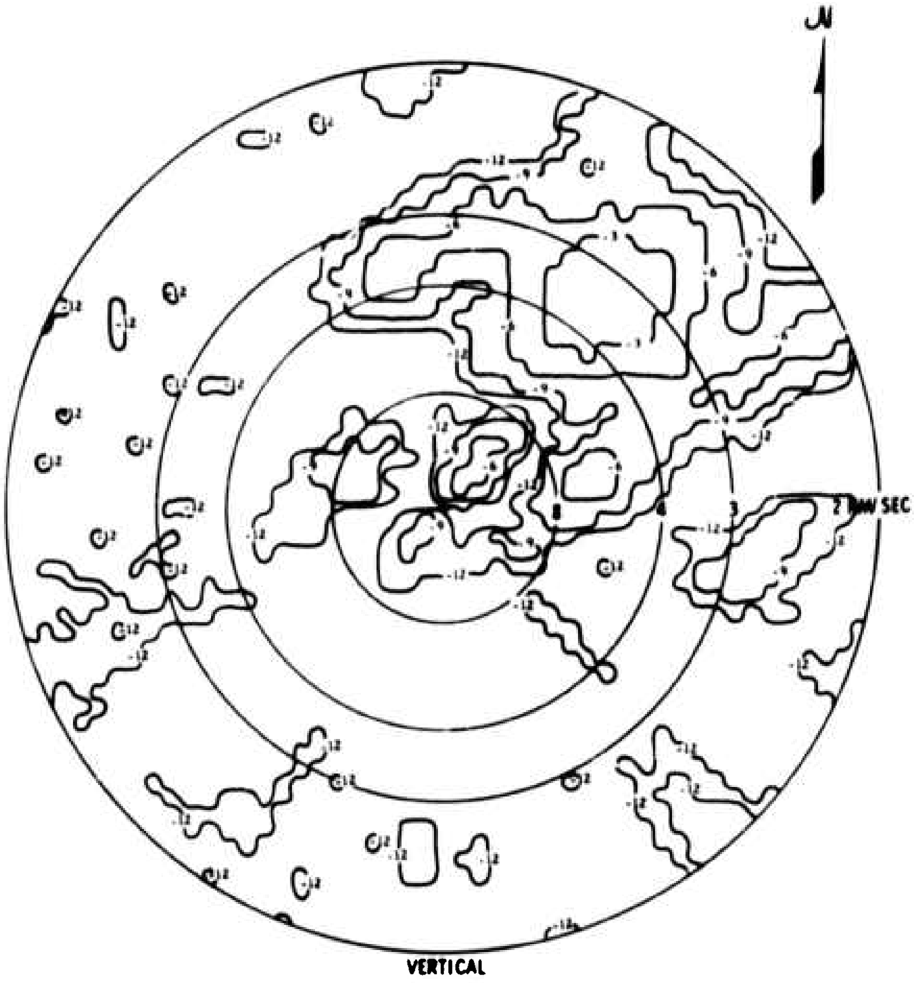

Figure IV-1. Wavenumber Spectrum of Vertical Component at 0.06 Hz, 3 December 1966 Noise

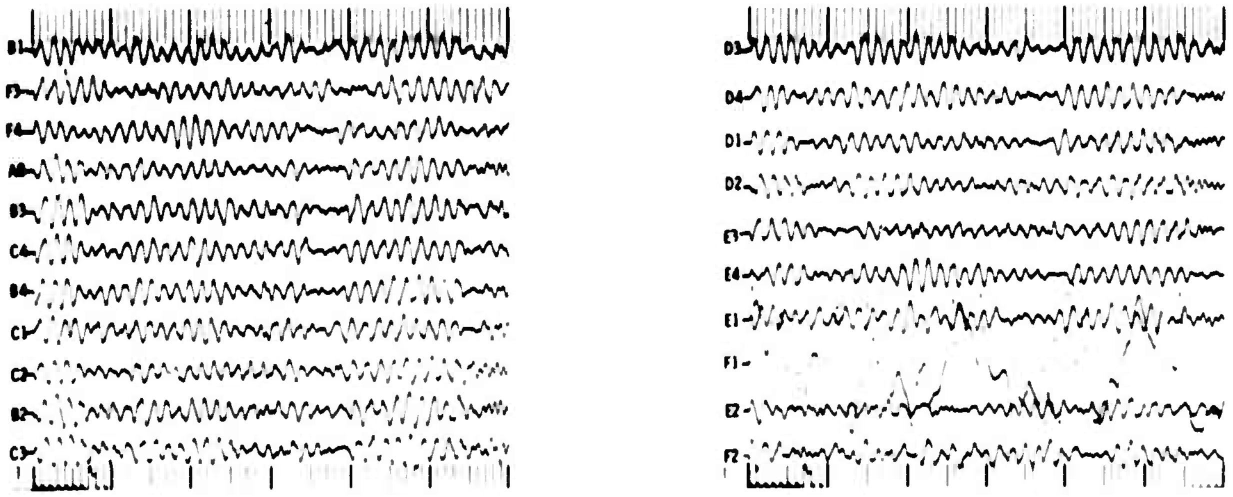

Figure IV-2. Vertical Component, 3 December 1966 Noise

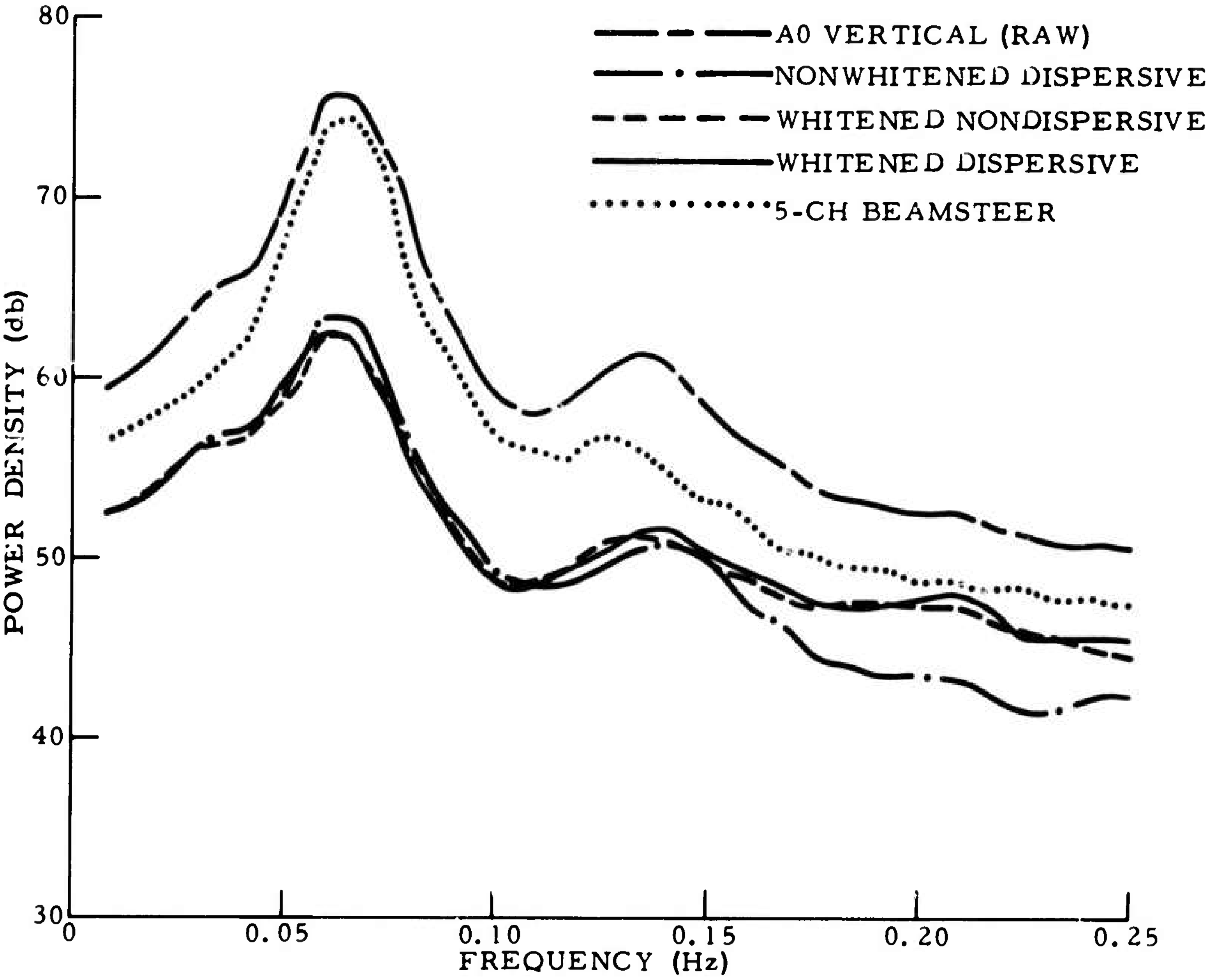

Figure IV-3. Power-Density Spectra of Raw and Processed Noise, 3 December 1966 Sample

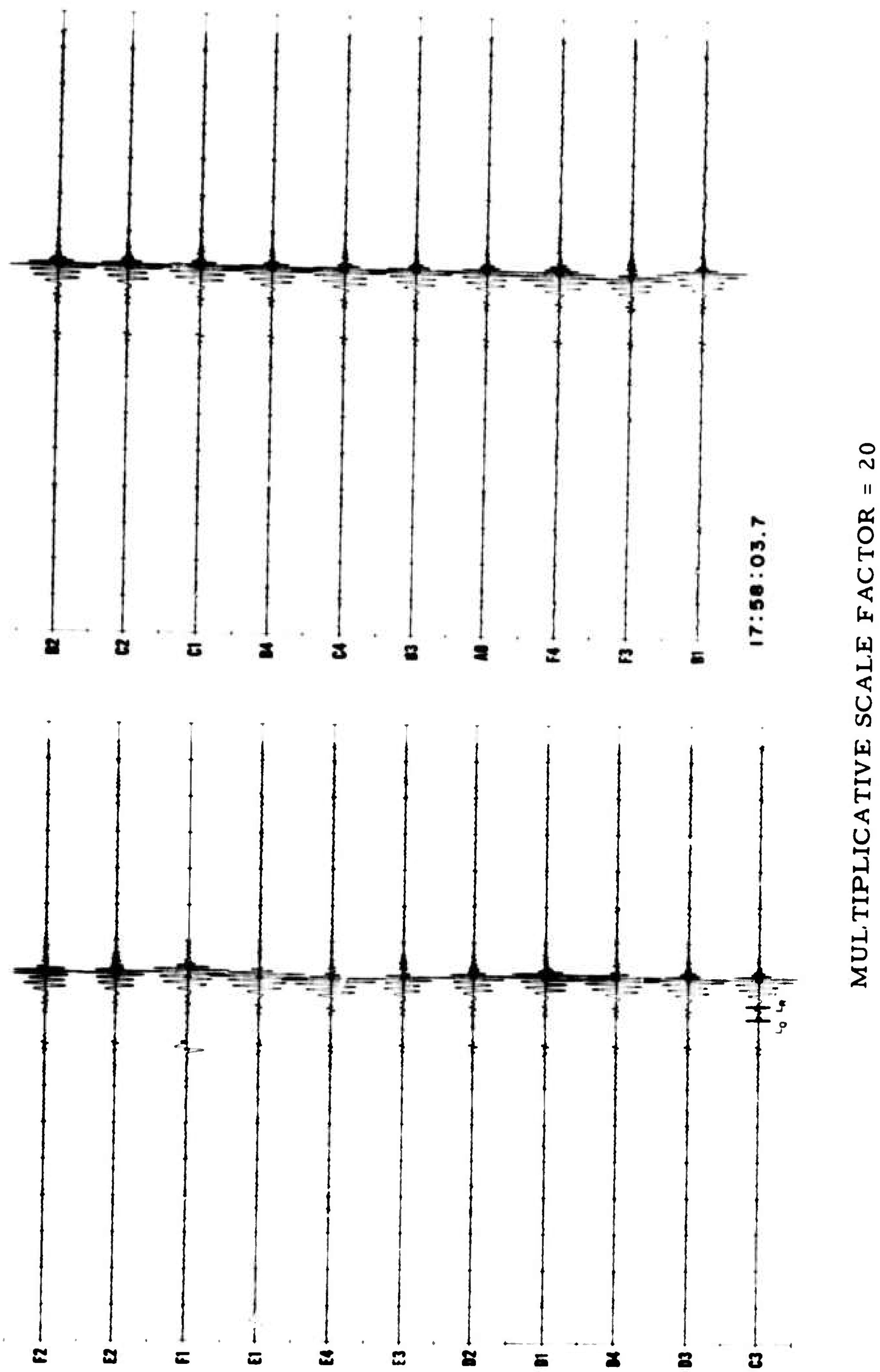

Figure IV-4. Signal, California Event, 3 December 1966

Three separate signal models were generated for MCF design (Table III-1). Each multichannel filter was a 5-channel and used the A- and D-ring vertical seismometers and 31 filter points. Signal models were generated according to the procedure described in Section III. All three designs were modeled from the A0 vertical noise and had Bartlett-smoothed spectra; they differed in that one was a dispersive model using prewhitened noise, another was a nondispersive model using prewhitened noise, and the third was a dispersive model using nonwhitened noise. The California event's azimuth was calculated to be S75°W, giving a signal/noise azimuthal separation of approximately 146°.

The power-density spectra of A0 vertical noise, the outputs of the three MCF processors applied to the noise alone, and the 5-channel beamsteer of the noise alone are shown in Figure IV-3. The beamsteer utilized the same seismometers as the multichannel filters.

Comparing the two processors generated from whitened data with the model generated from nonwhitened data, one sees that the model from unwhitened data has 3 to 5 db better noise rejection at the higher frequencies, approximately 1 db poorer rejection at the 0.06-Hz peak, and comparable rejection elsewhere. The two processors generated from whitened data have nearly identical noise-rejection capabilities over the entire frequency range. This is to be expected in view of the wide azimuthal separation of signal and noise and the fact that the signal is located at a relatively low noise region in K space. Figures IV-5 through IV-8 show the frequency-wavenumber responses of these two filters at 0.04 Hz and 0.06 Hz. The filters have very similar responses in the vicinity of the predominant noise peak.

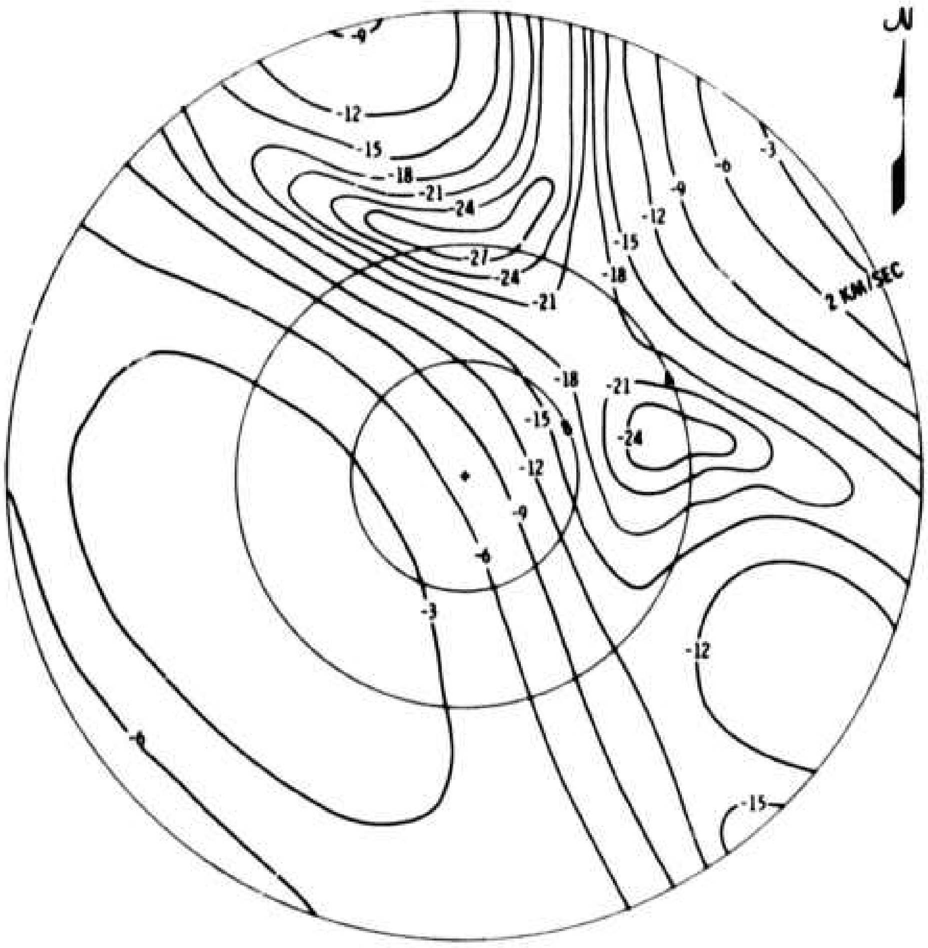

Figure IV-5. Wavenumber Response of 5-Channel MCF, Dispersive Signal Model, at 0.04 Hz

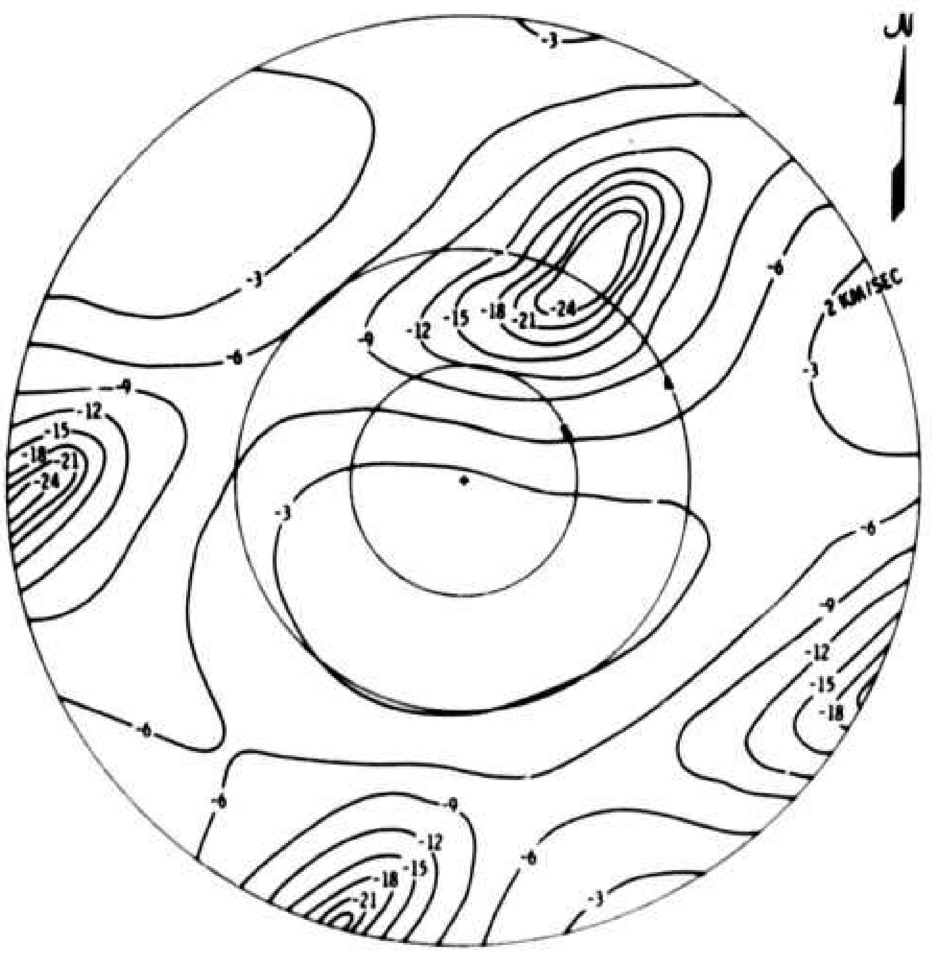

Figure IV-6. Wavenumber Response of 5-Channel MCF, Dispersive Signal Model, at 0.06 Hz

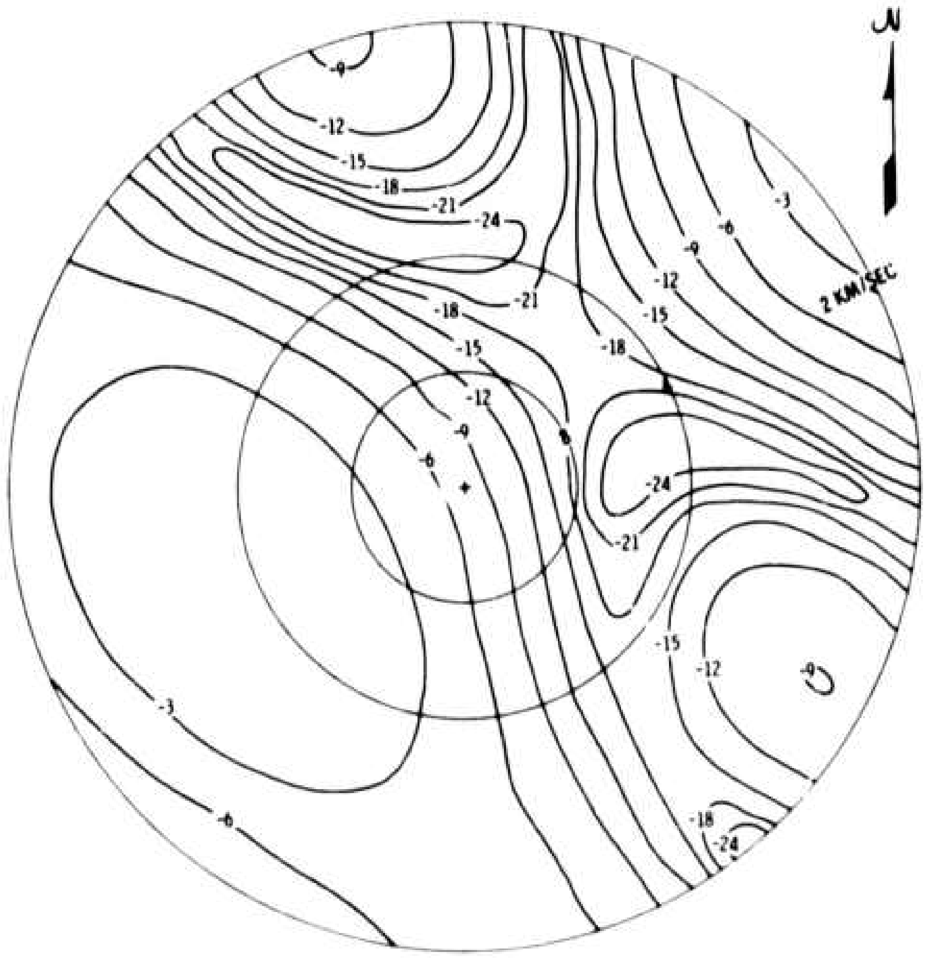

Figure IV-7. Wavenumber Response of 5-Channel MCF, Nondispersive Model, at 0.04 Hz

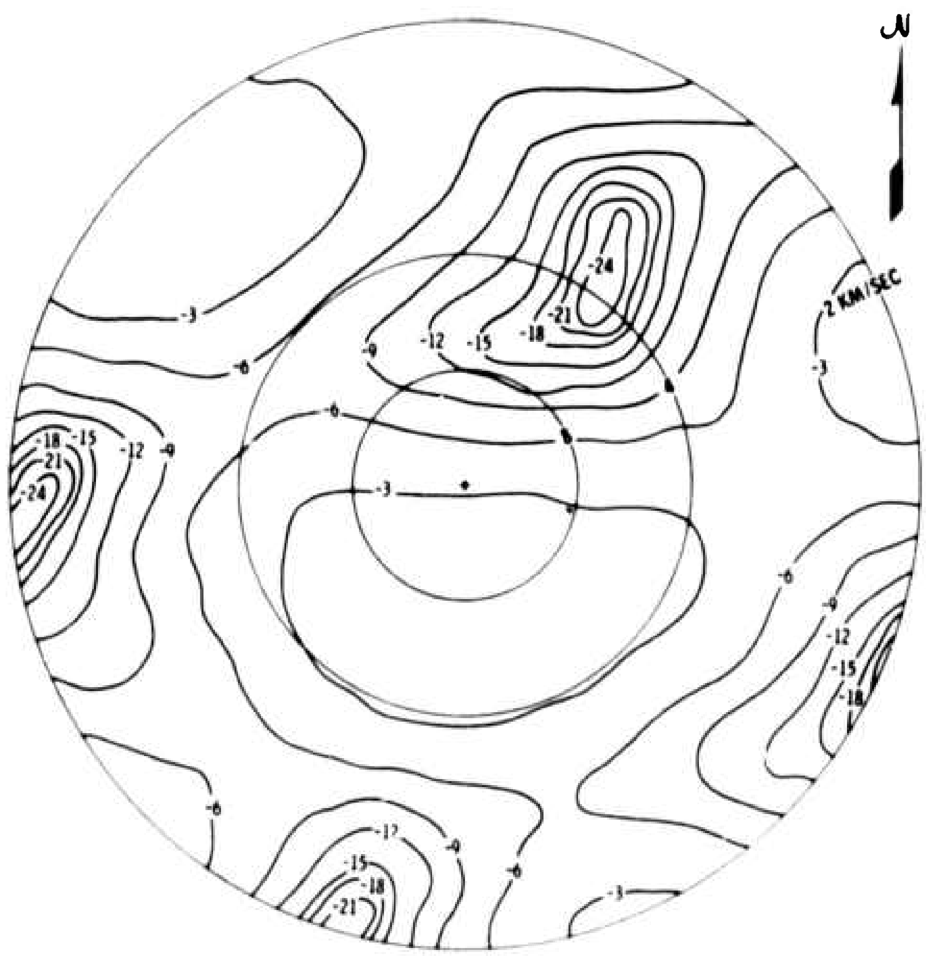

Figure IV-8. Wavenumber Response of 5-Channel MCF, Nondispersive Model, at 0.06 Hz

The beamsteer processor's noise-rejection ability is approximately 1 db in the vicinity of the 0.06-Hz peak and 2 to 5 db elsewhere. The relatively poor performance of the beamsteer at the lower frequencies is due to the strong sidelobes resulting from the widely spaced elements of the D ring. Figure IV-9 shows the wavenumber response of the A0 and D-ring straight sum at 0.06 Hz. When the array is steered to the signal, the high response peak to the northeast is moved inward and encompasses a large portion of the noise peak. It is evident from Figure IV-9 that, for the A0 and D-ring array, performance of the beamsteer for the extraction of Rayleigh phases from surface-mode noise is highly dependent on the relative positions of the signal and noise sources. The multichannel filter is less dependent on the relative positions.

Figure IV-10 shows the results of applying the processors to the California event. There is very good signal preservation by each of the processors; this is as expected in view of the good signal similarity among the elements used.

The use of a dispersive model for this signal does not appear to possess any detectable advantage over the use of a nondispersive model. As shown by Figures IV-5 and IV-7, both MCFs develop a rather broad response peak in the vicinity of the signal location in K space; thus, small errors in the signal-model velocities would not materially affect the filter's signal-preservation capability. Furthermore, most of the energy of the signal appears to be in a rather narrow frequency band, so any distortion that might occur at frequencies of rather low energy might not be visually detectable.

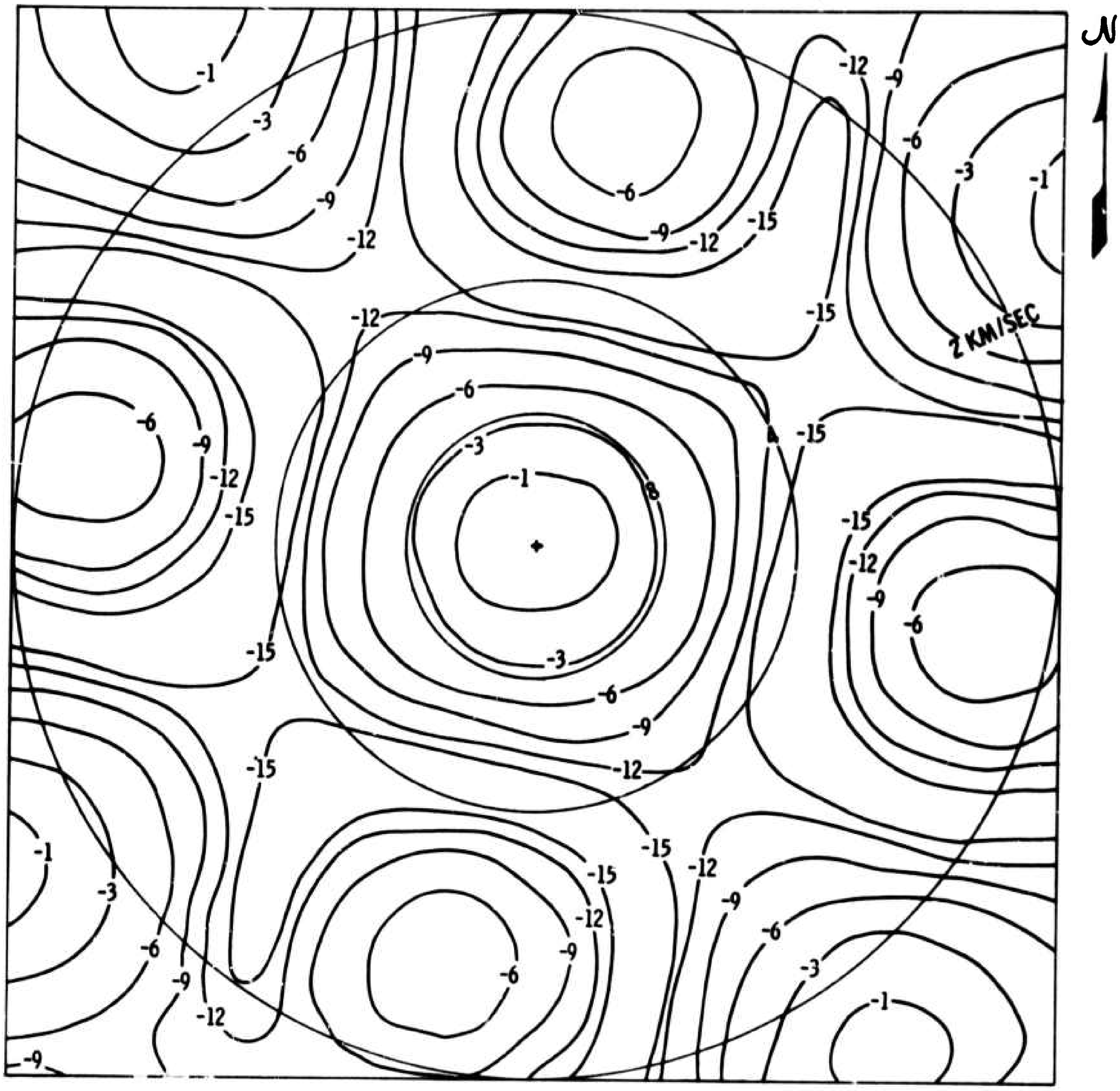

Figure IV-9. Wavenumber Response of 5-Channel Straight Summation at 0.06 Hz

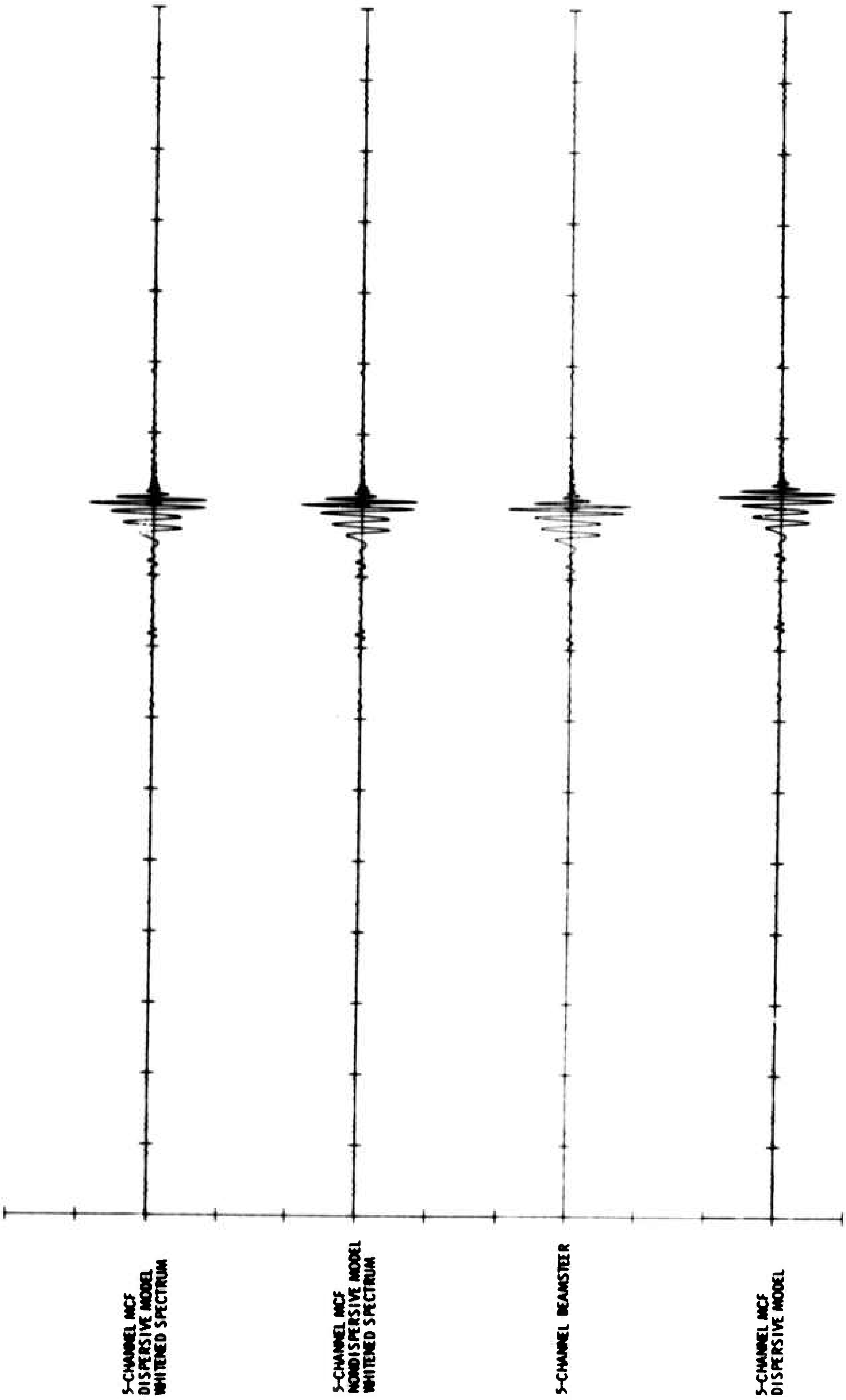

Figure IV-10. Signal Output of 5-Channel Processors, California Event

Whitening of the noise spectrum from which the signal model is generated does not appear significantly beneficial to this signal. Whitening of the data yields a filter which tends to have a more uniform response at all frequencies. Thus, the main difference between a filter generated from whitened data and a filter generated from nonwhitened data would occur at those frequencies having relatively low energy, so detection of this difference by purely visual means would be difficult.

C. SMALL AZIMUTHAL SEPARATION

To investigate the performance of beamsteer and MCF processors for the condition of small azimuthal separation of signal and noise, the 7 February 1967 noise sample and the Hokkaido event signal were chosen.

Figure IV-11 shows the wavenumber spectrum at 0.05 Hz for the vertical component of the noise. Dominating the spectrum at approximately N50°W is a point-like source having a velocity of about 3.5 km/sec.

Figure IV-11. Wavenumber Spectrum of Vertical Components at 0.05 Hz, 7 February 1967 Noise

Figure IV-12 shows the power-density spectrum of A0 vertical and the power-density spectral results of processing.

The signal for the Hokkaido event arrives at LASA at an azimuth of N47.7°W, giving a signal and noise azimuthal separation of about 2.3°. The signal is relatively strong and has moderately good similarity across the array. Signal traces are shown in Figure IV-13.

Five different processors applied separately to the noise and signal can be distinguished as follows:

- 5-channel beamsteer, A0 and C-ring verticals
- 9-channel beamsteer, A0 and C- and D-ring verticals
- 5-channel MCF, A0 and C-ring verticals, dispersive model
- 9-channel MCF, A0 and C- and D-ring verticals, dispersive model
- 9-channel MCF, A0 and C- and D-ring verticals, nondispersive model

The multichannel filters were designed as described in Section III. All had 21 filter points.

Figure IV-12 shows the power-spectral densities of the processor noise outputs. Over the whole frequency range, each MCF outperforms the beamsteer utilizing the same channels. In fact, the 5-channel MCF outperforms the 9-channel beamsteer by as much as 2 db below 0.16 Hz; above this frequency, the two are comparable.

None of the processors does particularly well at the 0.06-Hz peak. The noise-power reduction is approximately 1 db for the beamsteer processors, nearly 4 db for the 5-channel MCF, and 6 db for each of the 9-channel multichannel filters. Performance of each processor improves at the 0.11-Hz peak as well as at the 0.15-Hz peak.

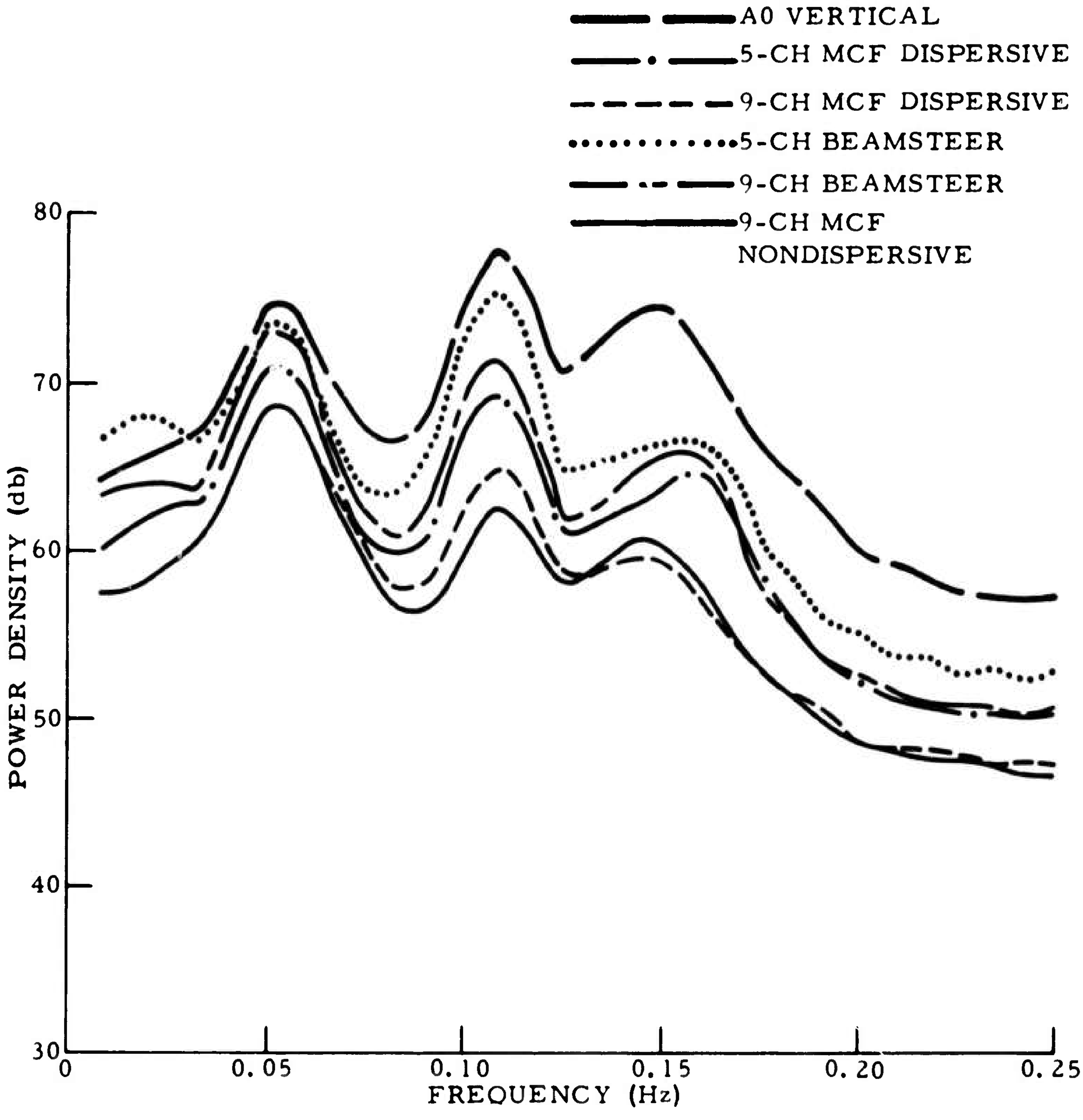

Figure IV-12. Power-Density Spectra of Raw and Processed Noise, 7 February 1967 Sample

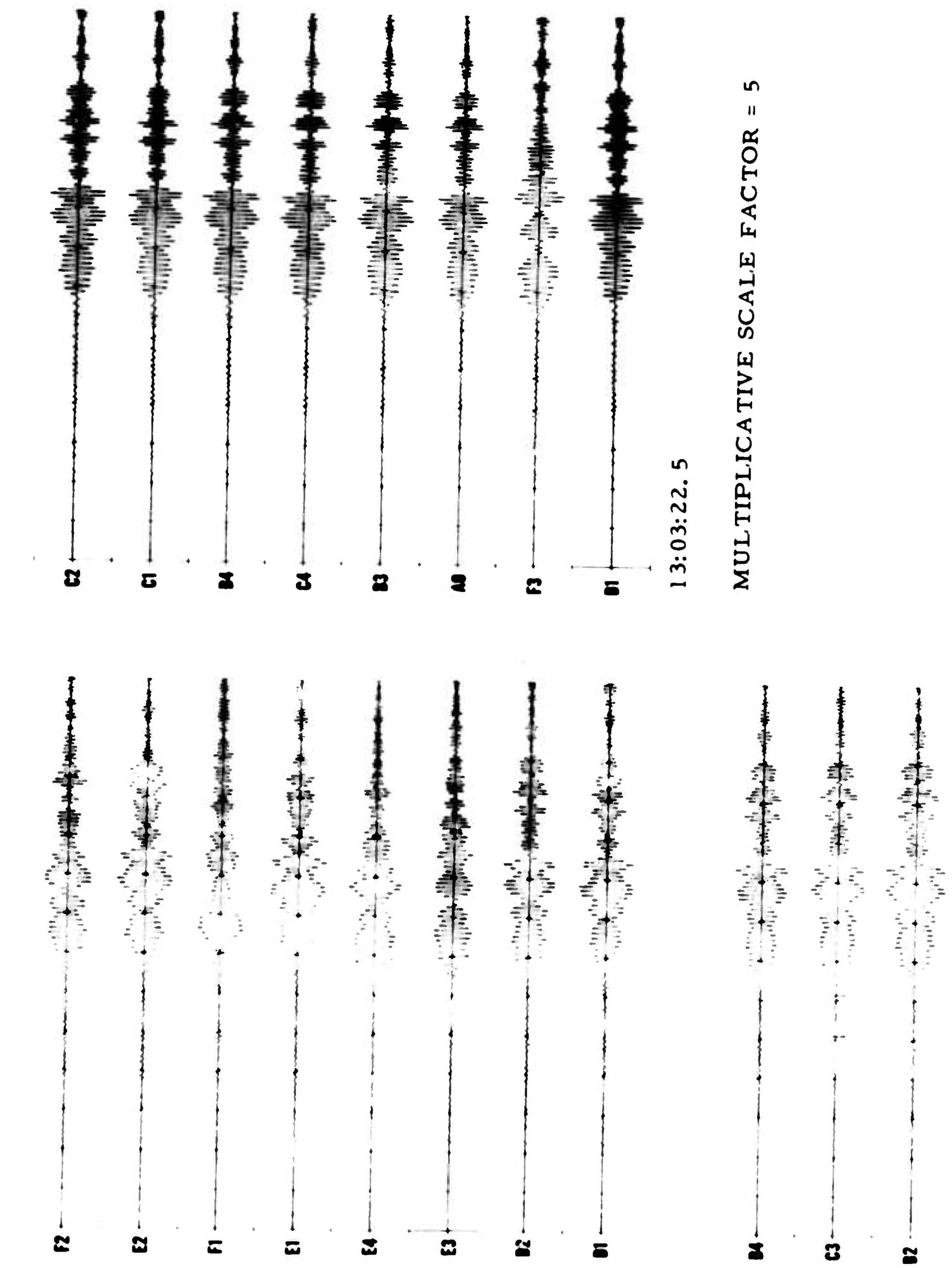

Figure IV-13. Signal Traces, Hokkaido Event

The two 9-channel multichannel filters have almost identical responses in the vicinity of the 0.06-Hz peak; this is near the frequency at which the delay-vs-frequency curves for the signal models coincide. Near 0.11 Hz, the filter generated from a nondispersive signal model achieves 2 db more noise-power reduction than does the filter designed from a dispersive signal model. Near 0.15 Hz, the latter outperforms the former by 1 db. At other frequencies, the two filters are essentially equivalent.

Figure IV-14 shows the outputs of the processors when applied to the Hokkaido event. Although small differences among the traces are visually discernible, the signal-preservation capabilities of the processors are essentially equivalent for this signal.

Because the noise power is concentrated in K space and the signal and noise have azimuthal proximity, the 9-channel filter would be expected to attempt generation of a sharp response peak at the signal location. In such a case, a small difference between signal velocity and model velocity could result in serious signal degradation at the output of the filter. The signal outputs (Figure IV-14) of the two 9-channel multichannel filters indicate no serious degradation.

Figures IV-15, IV-16, IV-17, and IV-18 show wavenumber responses of 5-channel and 9-channel MCFs; the latter two illustrations show that the K-plane responses of the dispersive-model 9-channel filter at the indicated frequencies are rather narrow azimuthally but are elongated radially. Thus, the responses are nearly flat for a wide range of velocities at these frequencies. This could explain the nearly identical signal responses of the two 9-channel multichannel filters.

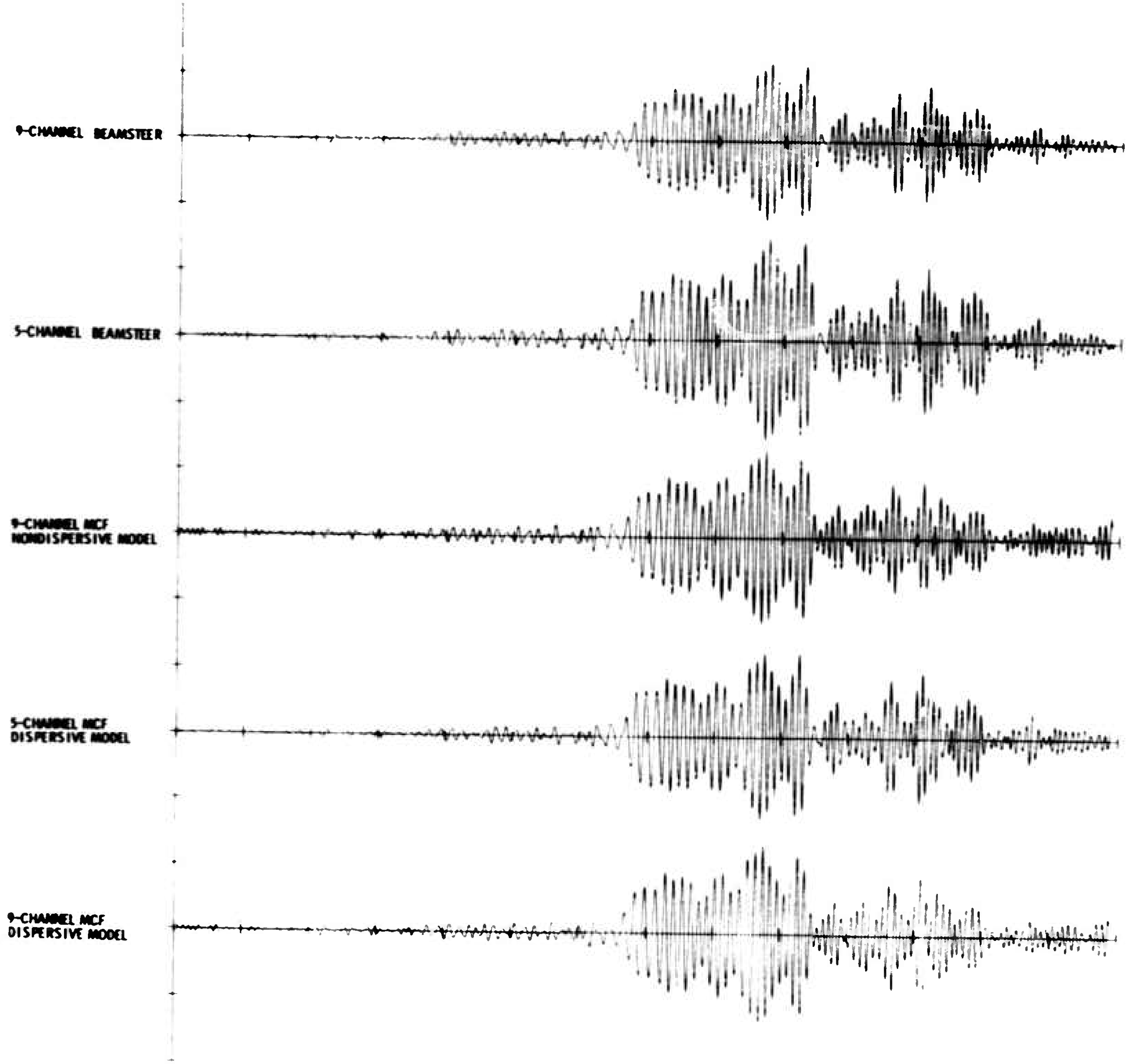

Figure IV-14. Signal Output of 5- and 9-Channel Processors, Hokkaido Event

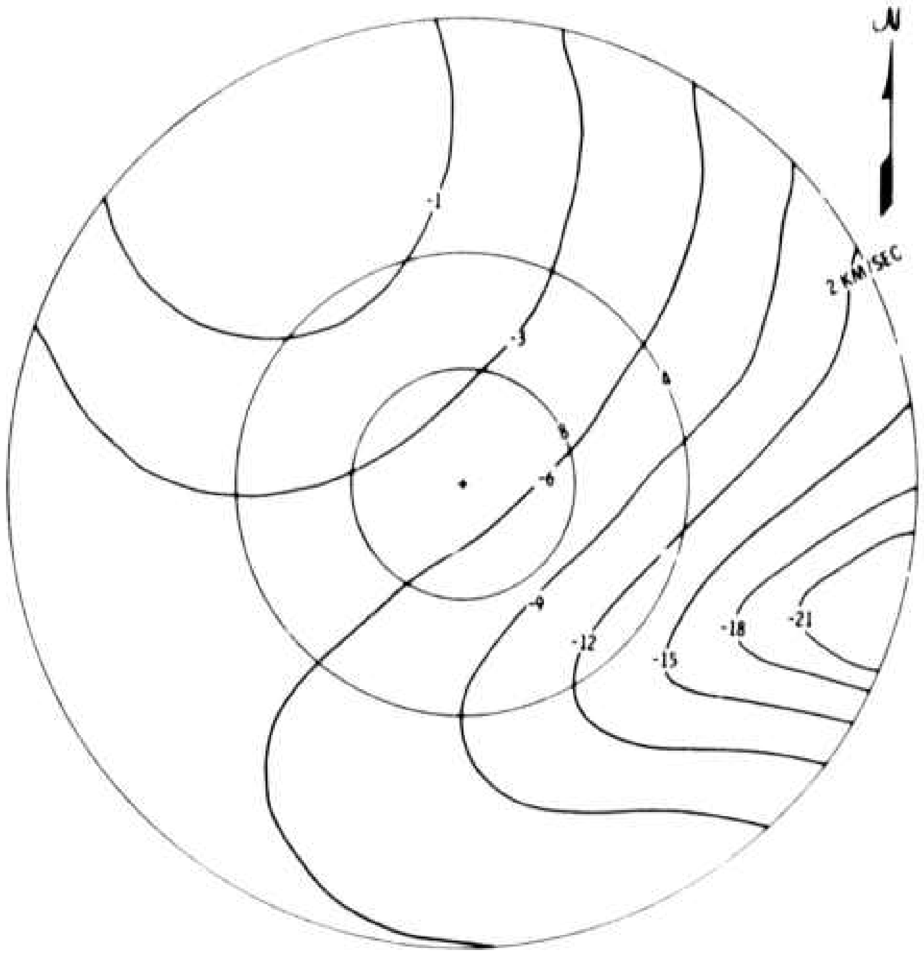

Figure IV-15. Wavenumber Response of 5-Channel MCF, Dispersive Model, at 0.04 Hz

Figure IV-16. Wavenumber Response of 5-Channel MCF, Dispersive Model at 0.06 Hz

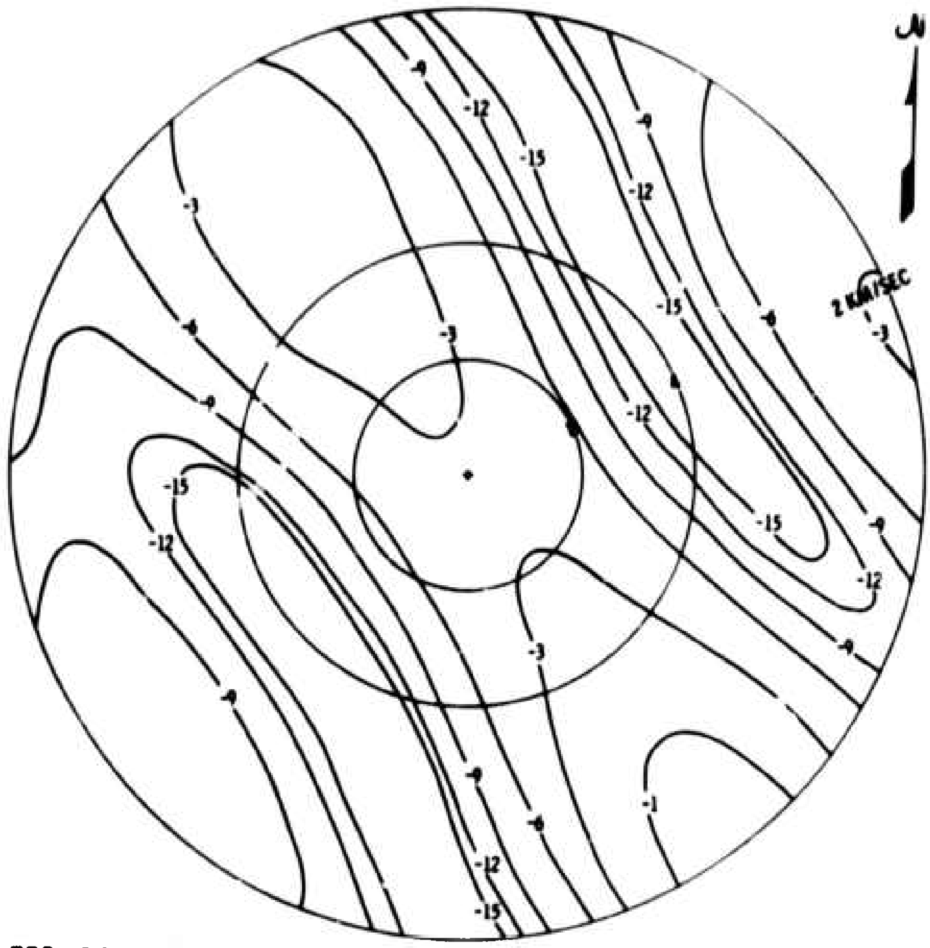

Figure IV-17. Wavenumber Response of 9-Channel MCF, Dispersive Model, at 0.04 Hz

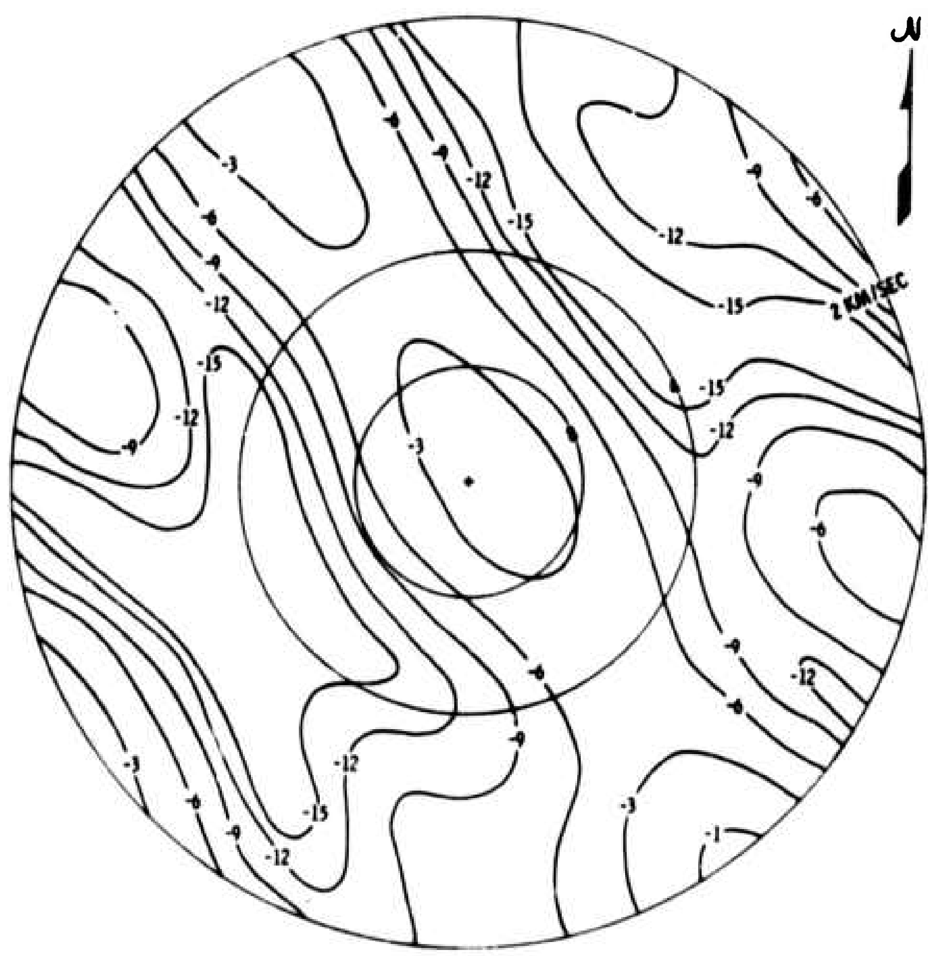

Figure IV-18. Wavenumber Response of 9-Channel MCF, Dispersive Model, at 0.06 Hz

D. ISOTROPIC NOISE PROCESSING

The 13 December 1966 noise sample is more nearly isotropic and of lower power than other winter samples studied. For this reason, this noise sample was used in conjunction with the New Hebrides signal in designing the processors.

Figure IV-19 shows the wavenumber spectrum of the noise sample at 0.06 Hz. At this frequency, there is a broad peak to the west and some smaller widely distributed peaks generally north and northeast. The power-density spectrum of the A0 vertical is included in Figure IV-20; the spectrum is relatively smooth and has fewer dominant peaks than the previous noise samples.

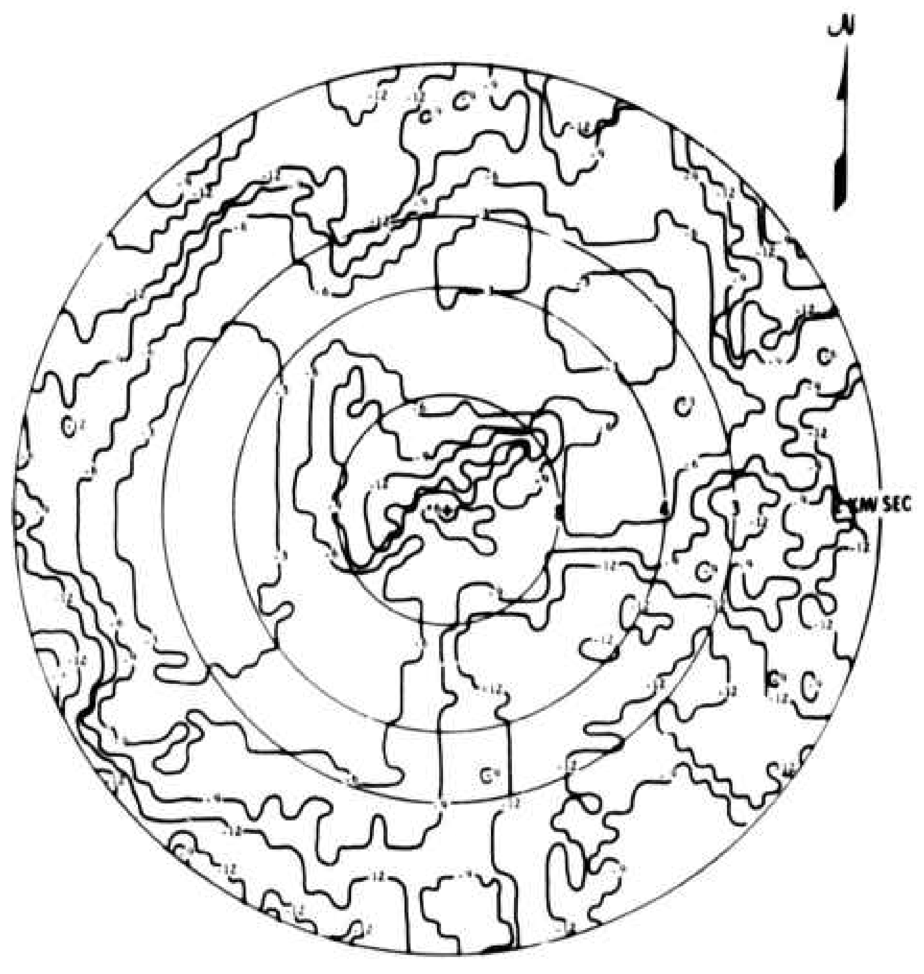

Figure IV-19. Wavenumber Spectr[illegible]m of Vertical Components at 0.06 Hz, 13 December 1966 Noise

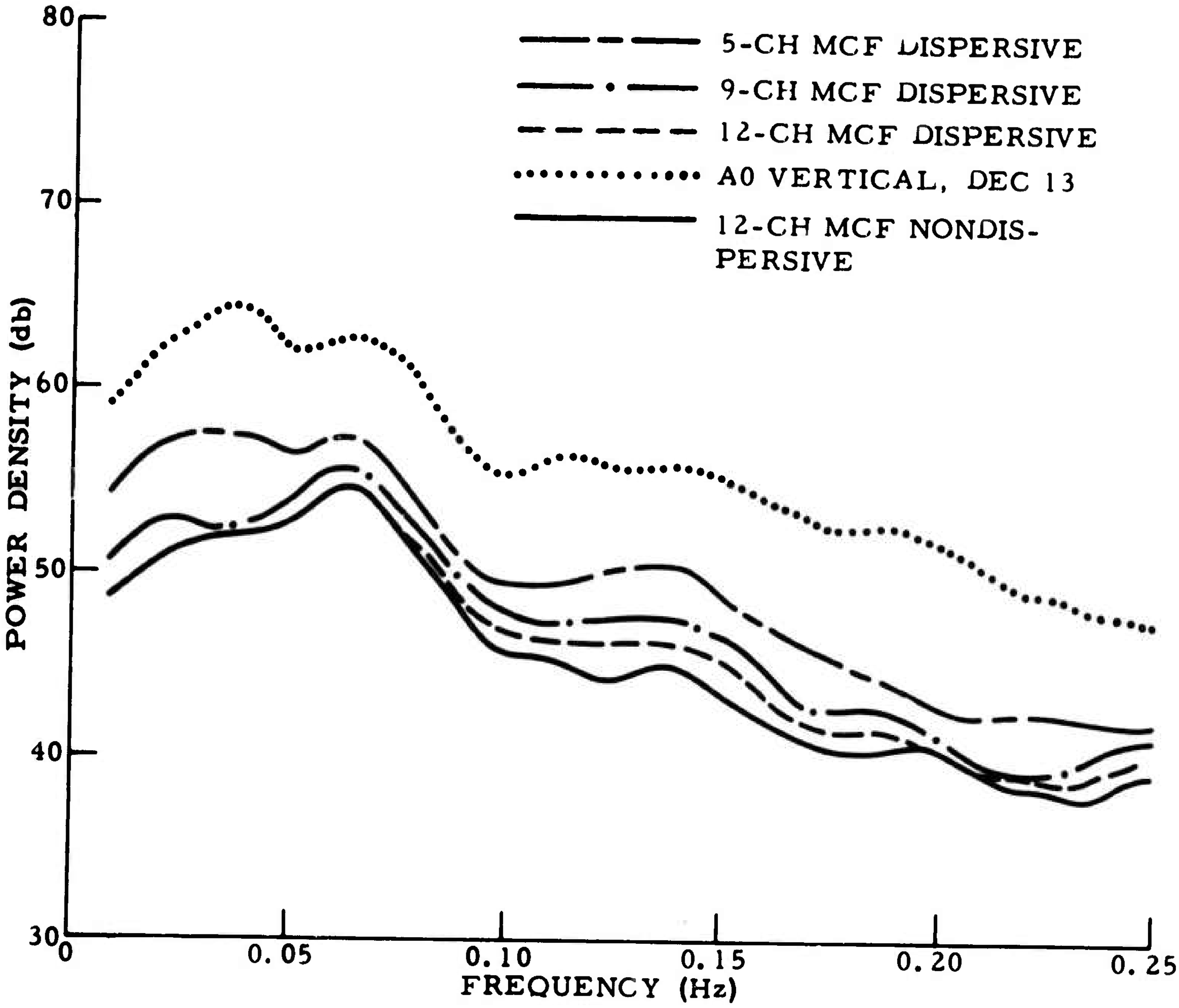

Figure IV-20. Power-Density Spectra of Raw and MCF Processed Noise, 13 December 1966

Figure IV-21 shows a segment of the vertical traces. The noise energy appears to arrive more uniformly in time than did that of the 3 December 1966 noise.

The New Hebrides signal, shown in Figure IV-22, is relatively strong and exhibits some features of dissimilarity across the array. Event azimuth is S77.5°W.

The seven processors designed to process the data can be designated as follows:

- 5-channel beamsteer, A0 and C-ring verticals
- 9-channel beamsteer, A0, and C- and D-ring verticals
- 12-channel beamsteer, A0 and C-, D-, and E-ring (less E3) verticals
- 5-channel MCF, A0 and C-ring verticals, dispersive signal model
- 9-channel MCF, A0 and C- and D-ring verticals, dispersive signal model
- 12-channel MCF, A0 and C-, D-, and E-ring (less E3) verticals, dispersive signal model
- 12-channel MCF, A0 and C-, D-, and E-ring (less E3) verticals, nondispersive models

Multichannel filters were designed as described in Section III. All used 21 filter points.

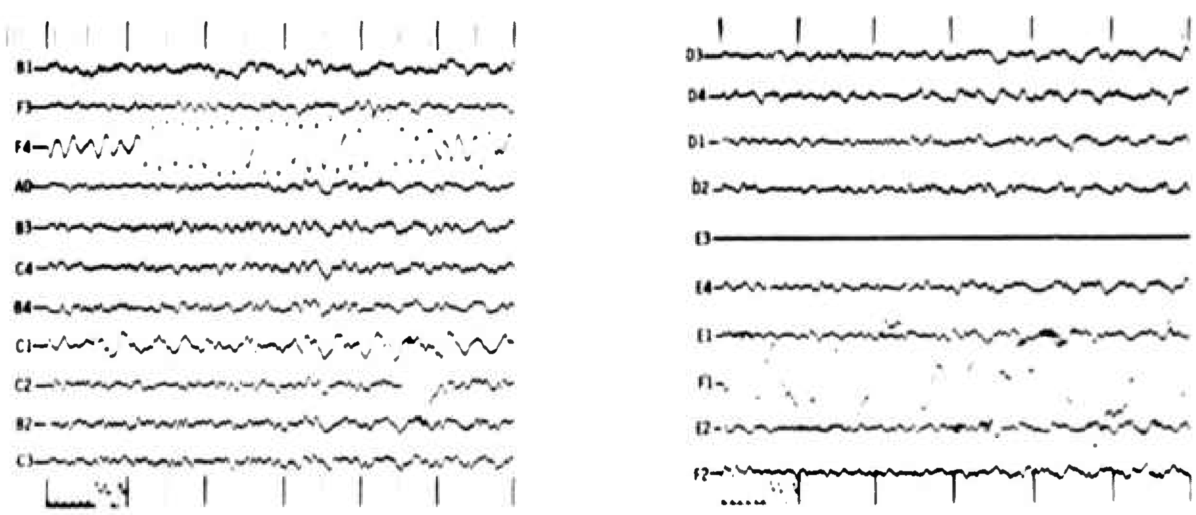

Figure IV-21. Portion of 13 December 1966 Noise Sample

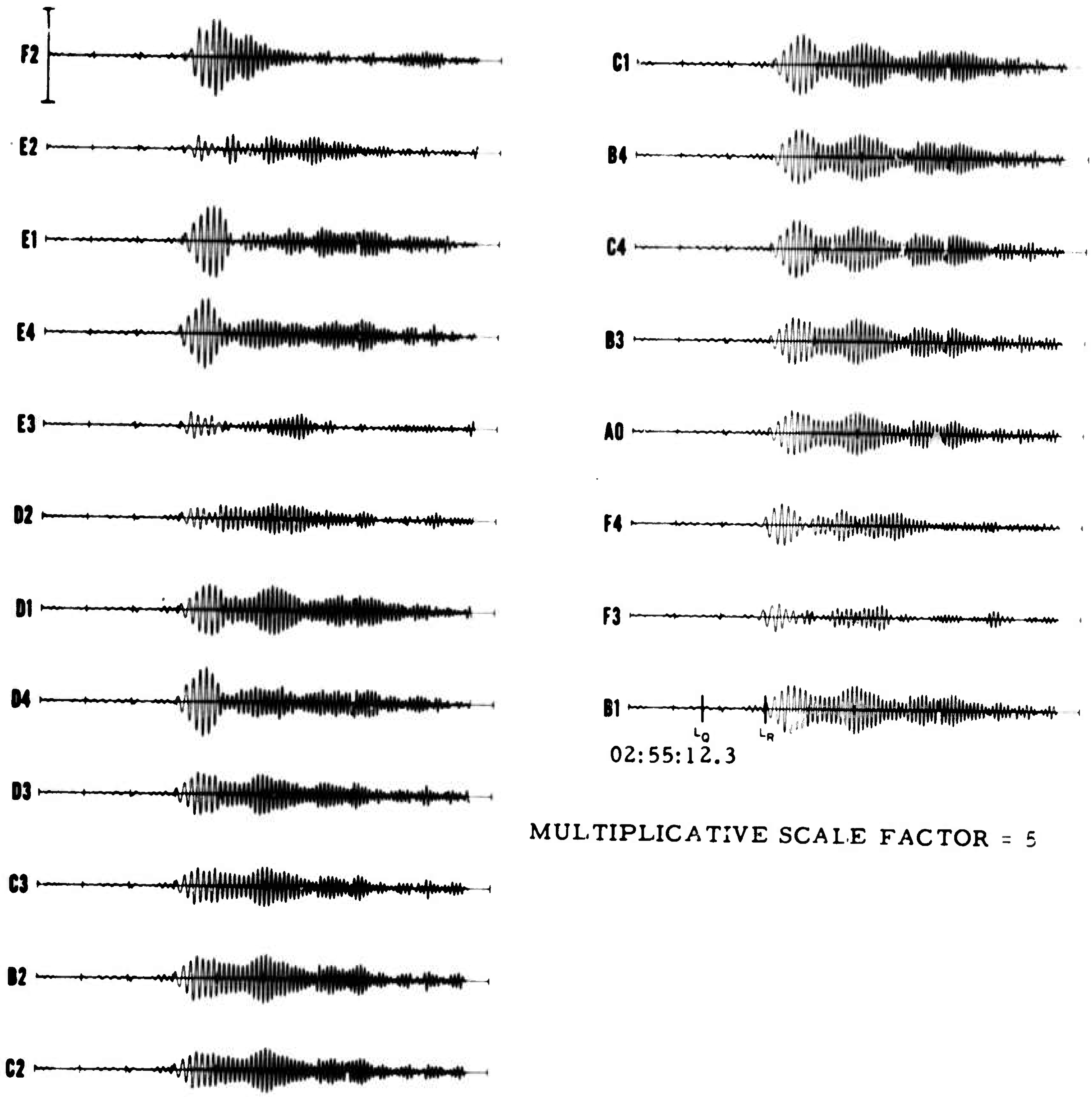

Figure IV-22. New Hebrides Event

Figures IV-20 and IV-23 show the power-density spectra of the processor outputs when applied to the noise. In each case, the multichannel filter outperforms its beamsteer counterpart; i.e., the beamsteer processor utilizing the same seismometers. At certain frequency bands, however, the beamsteer using a larger number of channels outperforms the MCF using a smaller number of channels. For example, the 9-channel beamsteer outperforms the 5-channel MCF above 0.11 Hz; likewise, the 12-channel beamsteer outperforms the 9-channel MCF above 0.10 Hz. The 12-channel beamsteer surpasses the 5-channel MCF over the entire frequency range with the exception of a small region around 0.08 Hz.

Each processor achieves nearly uniform noise-power reduction across the full frequency range. The 5-channel MCF yields 5 to 8 db reduction, and the 9-channel MCF yields 7 to 11 db reduction; each of the 12-channel multichannel filters yields 8 to 12 db reduction. Beamsteer processors also achieve nearly uniform noise-power reduction across the full frequency range; this uniformity of noise reduction across the frequency spectrum is a consequence of the smooth frequency spectrum and the isotropic character of the noise field in K space.

Both 12-channel multichannel filters have nearly identical performances to 0.08 Hz while, at the higher frequencies, the MCF designed from a nondispersive signal model is somewhat the better of the two.

Figure IV-24 shows the outputs of the processors applied to the New Hebrides signal. Again, the visual differences among the traces are slight.

As in the previous cases, there appears to be no significant differences between the signal outputs when using a dispersive or a nondispersive signal model.

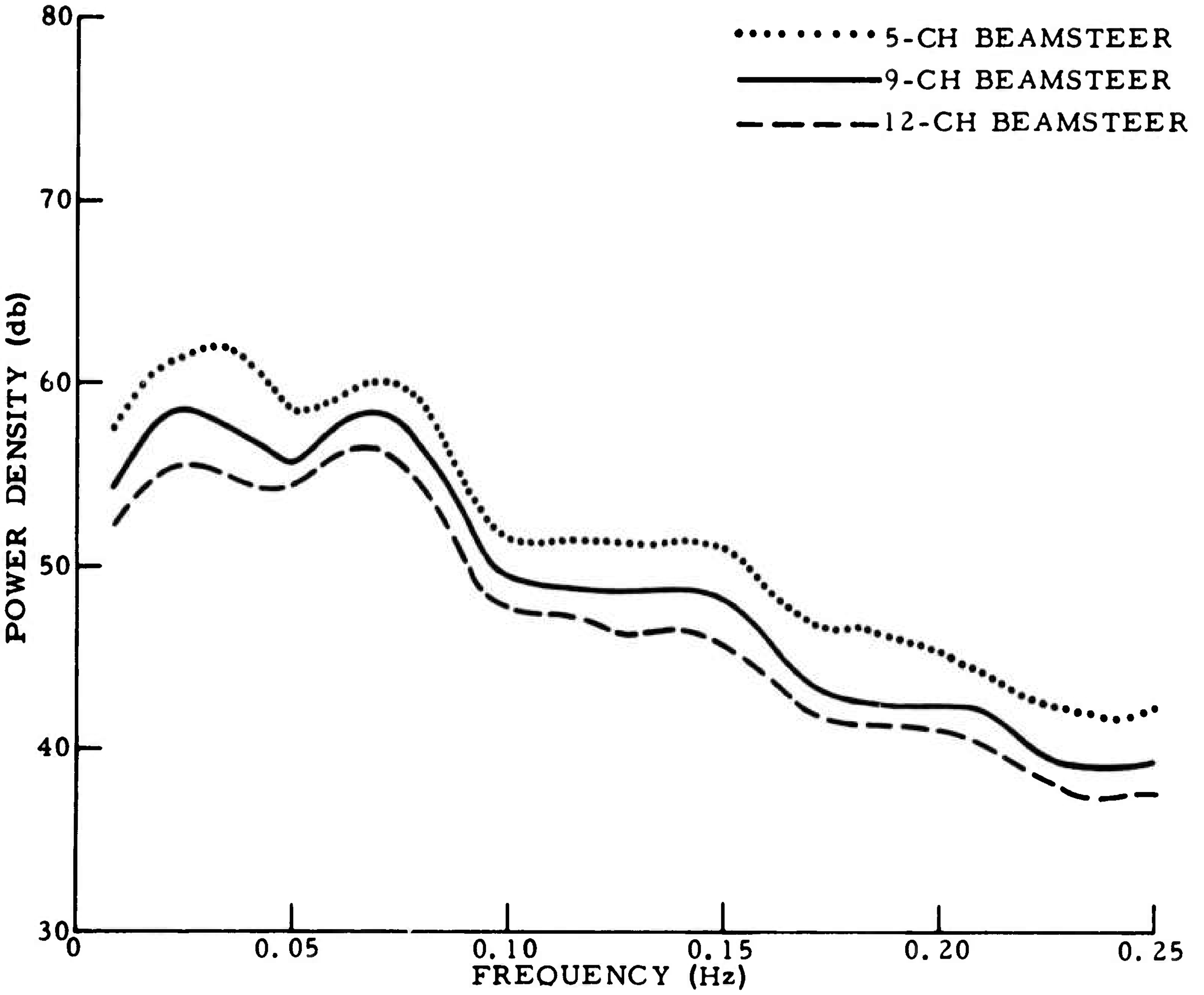

Figure IV-23. Power-Density Spectra of Beamsteer Outputs, 13 December 1966 Noise

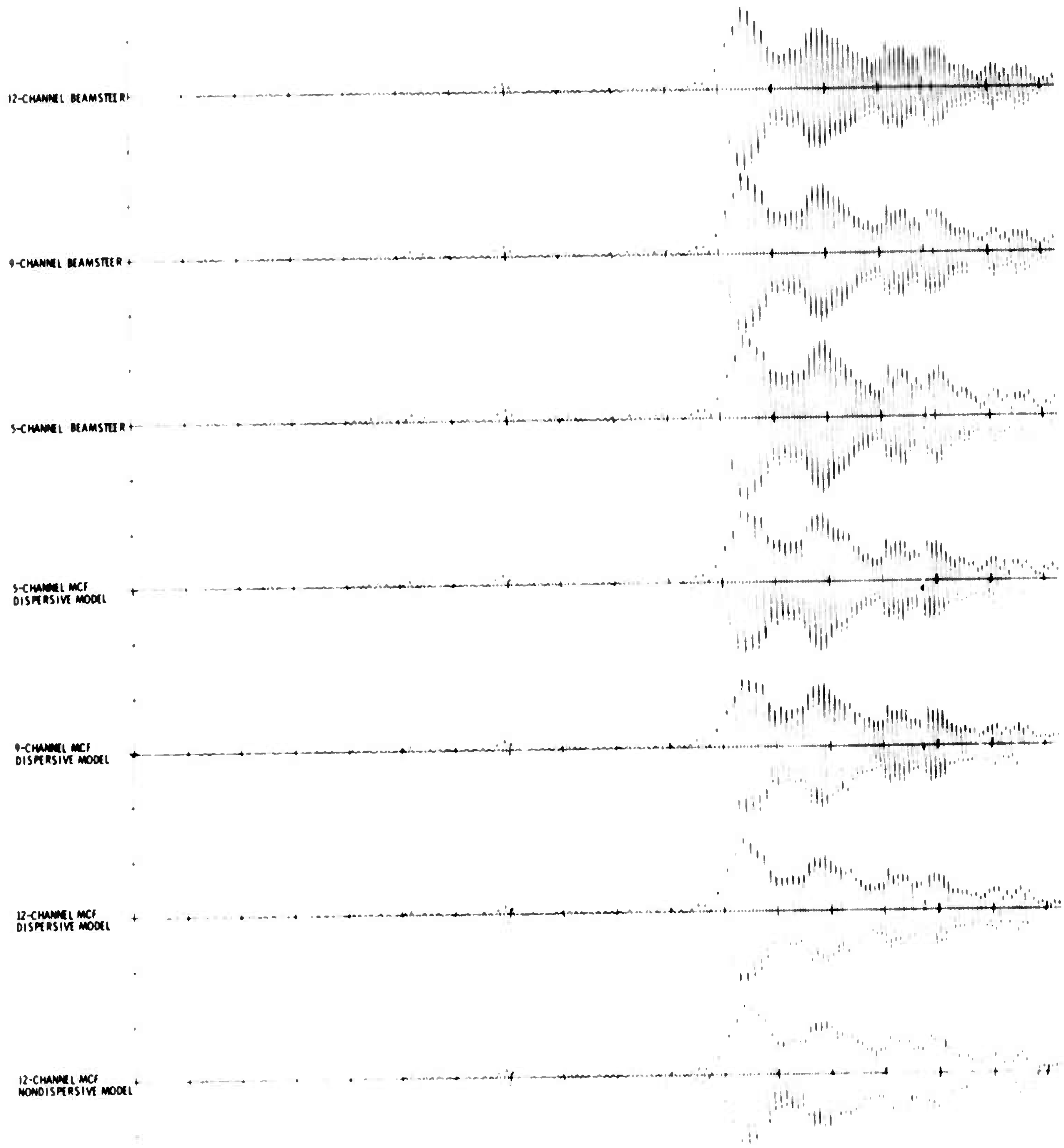

Figure IV-24. Processed Signal, New Hebrides Event

SECTION V
CONCLUSIONS

The noise-event combinations and processing schemes discussed in the previous sections were contrived to simulate specific processing environments. While they represent a small sampling of the possible environments, it is expected that the results, coupled with previous studies of long-period noise and Rayleigh-wave properties, are sufficient to support rather general conclusions regarding Rayleigh-wave extraction from ambient noise.

In all cases, the multichannel filter outperformed the beamsteer processor utilizing the same seismometers. It is sufficient to base performance on noise-power reduction alone, since the signal performances of all processors were essentially equivalent. The improvement of the MCF over the beamsteer varied with array geometry and signal/noise environment. At 0.06 Hz, improvement ranged from approximately 11 db for the A0 and D-ring processor applied to the 3 December 1966 noise down to 2 db for the A0 and C-ring processor applied to the 7 February 1967 noise. The most significant improvements of the MCF processors over the summation processors occurred for the smaller arrays (60-km aperture or less). For the broadly distributed noise field (13 December 1966 sample), the 9-channel MCF outperformed the 12-channel beamsteer by 1 to 3 db below 0.1 Hz.

The performance of each processor was improved by increasing the size and number of the elements of an array. Adding the D ring to the A0 and C ring yielded 1- to 5-db improvement below 0.1 Hz for the MCF processors. Further addition of the E ring yielded approximately 1-db improvement in this same range.

For the events studied, use of a dispersive signal model in MCF design did not yield significant improvement over the use of a nondispersive signal model. This fact becomes particularly important when considering on-line adaptive processing. Even for off-line MCF processing, the nondispersive design is easier to implement.

From the results and observations, a good compromise design for the extraction of Rayleigh waves from ambient noise would appear to consist of a 9-element 60-km-aperture vertical long-period array. Summation processing might be adequate for strong signals but, for weaker signals, the advantages of MCF processing could be exploited.

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13. ABSTRACT

This report presents the results of an investigation of processing techniques for extracting long-period Rayleigh waves from ambient noise by using various geometries of the LASA long-period vertical array. Delay-and-sum and multichannel signal extraction are the processing schemes evaluated. Results indicate that for a given array geometry, the multichannel signal-extraction filter gives greater noise-power rejection than the corresponding beamsteer processor. For a small array having few elements, MCF gain over summation processing is very significant; below approximately 0.1 Hz, gain is 3 to 10 db. For small-aperature arrays (less than 60 km), beamsteering does not give $\sqrt{N}$ amplitude rejection of noise below 0.1 Hz; furthermore, beamsteering of this type of array can sometimes produce adverse effects due to large sidelobes in the beamforming gain pattern. The 9-channel MCF is significantly superior to the 5-channel MCF. Addition of sensors outside a 9-channel 60-km array gives very little additional noise rejection when using MCF processing. Use of a dispersive signal model in the multichannel filter design yields no significant improvement over the use of a nondispersive model. For point-like sources, the noise-reduction capabilities of each processor are a function of signal and noise azimuthal separation, being generally least for small separation. Signal distortion appears negligible for all processors studied.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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LASA						
Long-Period Rayleigh Wave Extraction						
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